SEDIMENTARY EXHALATIVE ZN-PB-AG DEPOSITS
(MODEL 31a; Briskey, 1986)

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SUMMARY OF RELEVANT GEOLOGIC, GEOENVIRONMENTAL, AND GEOPHYSICAL INFORMATION

Deposit geology

Lens-like bodies of stratiform sulfide minerals (lead, zinc, ± iron) as much as a few tens of meters in thickness are interbedded with fine-grained dark clastic and chemical sedimentary rocks. These deposits may have large lateral extent (hundreds of meters to kilometers). Mineralized rock varies from a single layer to numerous bodies that may be vertically stacked or lateral equivalents. The most common associated sulfate mineral is barite which may be peripheral to or stratigraphically above the deposit (Rammelsberg and Meggen, Germany; Tom, Yukon Territory; Lady Loretta, Australia; and Red Dog, Alaska), or it may form crudely segregated mixtures with sulfide minerals (Cirque, British Columbia). Many deposits have no associated barite (HYC, Australia; Sullivan, British Columbia; and Howard's Pass, Yukon Territory). Stockwork, disseminated, or vein-type ore, interpreted as feeder zones to stratiform mineralized rock, are sometimes found underlying or adjacent to stratiform ore and are sometimes accompanied by alteration of footwall rocks (fig. 1). U.S. Bureau of Mines (1993) statistics show that in 1993 the two mines in the United States with greatest zinc output were Red Dog, Alaska and Balmat, N.Y. In 1994, the Red Dog mine produced 533,500 t of zinc concentrate with an average grade of 55.8 weight percent zinc (Mining Journal, 1995). Mines in the Balmat district produced 499,000 t in 1993. Both mines also produce lead and silver.

Examples

Red Dog, Lik, and Drenchwater (Alaska); Balmat (N.Y.); Meggen and Rammelsberg (Germany); Faro and other deposits in the Anvil district, Tom, Jason, and Howard's Pass (Yukon Territory); Cirque and Sullivan (British Columbia); Lady Loretta, McArthur River, Mount Isa, HYC, and Broken Hill (Australia); Navan, Silvermines, and Tynagh (Ireland); Black Mtn., Broken Hill, Big Syncline (South Africa); Zawar (India).
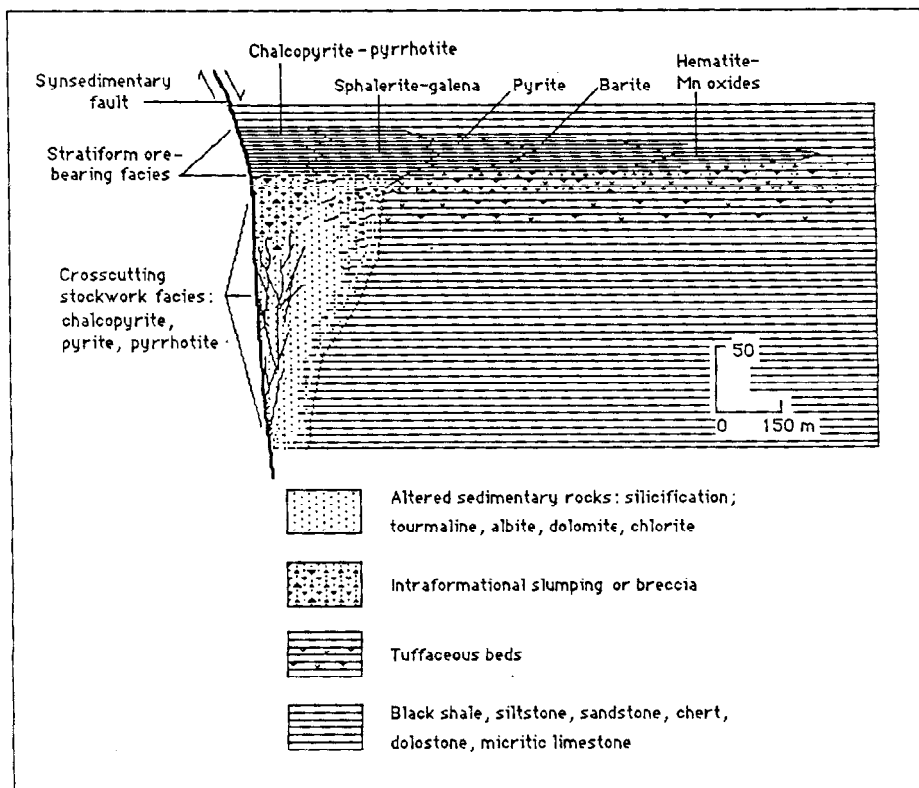

Figure 1. Diagrammatic cross section showing mineral zoning in sedimentary exhalative Zn-Pb deposits (from Briskey, 1986).
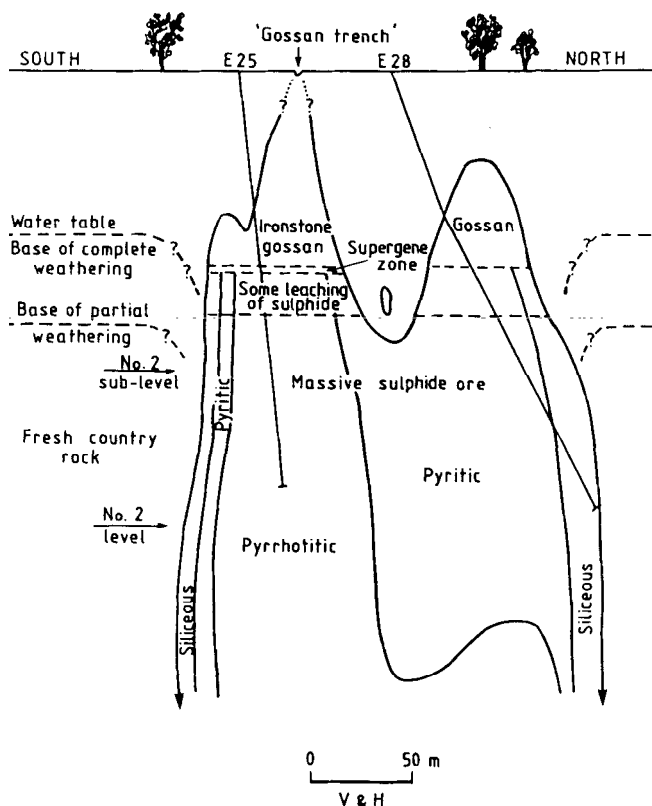
Figure 2. Longitudinal cross section showing development of supergene zone and iron-rich gossan (based on Elura deposit, Australia; from Taylor and others, 1984).

Spatially and (or) genetically related deposit types

Associated deposit types (Cox and Singer, 1986) include bedded barite deposits (Model 31b), stratabound lead-zinc in clastic rocks (Model 30a), Mississippi Valley type lead-zinc (Models 32a,b), sedimentary manganese (Model 34b), sedimentary phosphate (Model 34c), Besshi massive sulfide (Model 24b), Chinese-type black shale (Mo-Ag-As-Zn-Ni-PGE; Pasava, 1993).

Potential environmental considerations

(1) Deposits with no associated carbonate rocks or carbonate alteration minerals may have high potential for generation of natural acid drainage that contains high metal concentrations. Potential for acid-drainage generation may depend on (a) the amount of iron-sulfide present (which may vary from <5 to 80 volume percent among deposits), (b) the type of iron sulfide mineral(s) in the deposit (reactivity decreases from pyrrhotite to marcasite to pyrite) and (c) the extent to which the deposit is exposed to air and water. Water may contain thousands of mg/l sulfate; hundreds of mg/l iron; tens of mg/l aluminum; thousands to tens of thousands of μg/l zinc; thousands of μg/l manganese and lead; hundreds of μg/l cadmium, copper, and nickel; and tens of μg/l cobalt (Runnells and others, 1992; Kelley and Taylor, in press; EIS for Red Dog).
(2) Potential downstream environmental effects of natural acid drainage can be significant in magnitude and spatial extent (as far as 30 km downstream), especially if surrounding terrane is composed exclusively of fine-grained clastic rocks and volcanic rocks and no associated carbonate rocks (EIS for Red Dog).
(3) Deposits with associated carbonate rocks or abundant carbonate alteration minerals have limited potential for acid drainage generation (water pH usually neutral to slightly alkaline), and most metal concentrations are low; exceptions include as much as thousands of μg/l zinc in some natural water (Kelley and Taylor, in press).
(4) Iron-rich gossans, formed by oxidation and weathering, may develop above some deposits (fig. 2). Depending on wall-rock buffering capacity, iron content of ore, and metal-sulfur ratios of sulfide minerals, the gossan environment can be acidic (pH <5). Some gossans may contain a number of secondary lead-manganese minerals as well as secondary sulfates of iron, aluminum, and potassium (Taylor and others, 1984). These minerals are very soluble, can dissolve during periodic storms, and may lead to short term pulses of highly acidic, metal-bearing water.
(5) High-sulfide ore with elevated abundances of pyrrhotite that is exposed to air and water has potential for spontaneous combustion ("hot muck"), which generates sulfur dioxide (Brown and Miller, 1977; Good, 1977). Hot muck ignition is rare and can be avoided using proper blasting techniques.

Exploration geophysics

Gravity surveys can be used to identify and delineate the extent of barite-rich zones that may indicate associated base-metal sulfide deposits (Young, 1989; Hoover and others, 1994). Induced polarization methods have proven useful in exploration for some of these deposits (O'Brien and Romer, 1971; Cox and Curtis, 1977). Remote sensing images can be used to help identify associated gossans (Knepper, 1989). Magnetic and electromagnetic methods may help define the presence and extent of massive sulfide deposits, particularly those that contain abundant pyrite and (or) pyrrhotite. Constant source-audiomagnetotelluric methods have been used to help delineate the extent of ore in northwest Alaska (Young, 1989). Other geophysical methods may facilitate geologic mapping of these deposits (Edwards and Atkinson, 1986, p. 245).

References

Geology: Large (1981), Maynard (1983), Sangster (1983), Moore and others (1986), Turner and Einaudi (1986), Young (1989), Sangster (1990), Maynard (1991), and Schmidt (in press).
Environmental geology, geochemistry: Lee and others (1984), Runnells and others (1992), Gulson and others (1994), Prusty and others (1994), Sahu and others (1994), Kelley (1995), and Kelley and Taylor (in press).

GEOLOGIC FACTORS THAT INFLUENCE POTENTIAL ENVIRONMENTAL EFFECTS

Deposit size

Most deposits are 1.7 (90th percentile) to 130 (10th percentile) million tons; median deposit size is 15 million tons (Menzie and Mosier, 1986).

Host rocks

Host rocks consist of a variety of marine sedimentary rocks including: carbonaceous shale and chert (Howard's Pass, Yukon Territory; Red Dog and Lik, Alaska; and Sullivan, British Columbia), dolomitic shale or siltstone (HYC and Mount Isa, Australia; and Silvermines, Ireland), and micritic limestone (Meggen, Germany and Tynagh, Ireland). Turbidites and slump breccias are present locally; minor volcanic rocks, usually mafic, may be temporally, but not necessarily spatially, associated. Sangster (1990) indicates that tuff units are present within ore-hosting sequences at a number of deposits, including Meggen and Rammelsberg (Germany), Jason and Faro (Yukon Territory), and HYC (Australia). Many deposits and their host rocks have undergone metamorphism and deformation (Sullivan, British Columbia and Mount Isa and Broken Hill, Australia). Comparisons of host rock chemistry to average abundances in black shale (Vine and Tourtelot, 1970) show that host rocks for these deposits have relatively low sodium-potassium ratios and are characteristically depleted in cobalt, nickel, and copper and enriched in barium and manganese (Maynard, 1991).

Surrounding geologic terrane

The geologic terrane surrounding these deposits primarily consists of thick sequences of deep-water marine sedimentary rocks that include fine-grained clastic and carbonate rocks. Rocks may be metamorphosed (low to high-grades).

Wall-rock alteration

Stockwork and disseminated sulfide and alteration minerals (commonly silicified or iron-carbonate altered rocks that rarely contain tourmaline, albite, chlorite), which possibly represent the feeder zones of these deposits, are sometimes present beneath or adjacent to stratiform deposits (fig. 1). In some deposits, silicification is the dominant or only alteration (Meggen, Germany and Red Dog, Alaska). In others, alteration is less extensive and (or) carbonate-rich (Large, 1981). Large (1983) describes more subtle types of alteration near some deposits, including increased dolomite-calcite ratios (McArthur River, Australia; deposits in Ireland) and increased potassium feldspar-albite ratios in tuffs (McArthur River).

Nature of ore

Within stratiform mineralized rocks, sulfide minerals are generally fine-grained, and commonly form nearly monomineralic laminae several mm to cm thick that have continuity over large parts of the deposits. Some deposits are not laminated (Meggen, Germany and Red Dog, Alaska). Coarse-grained crustiform and comb-textured sulfide minerals may be present in feeder veins associated with stratiform ore. The overall sheet or lens-like morphology of stratiform ore suggests that these deposits formed, in highly restricted basins, by syngenetic to early diagenetic

processes at or below the seawater-sediment interface. Sphalerite, galena, and iron-sulfide minerals (pyrite, marcasite, and pyrrhotite) are the most common sulfide minerals, but chalcopyrite and sulfosalt minerals may also be present in minor amounts (Large, 1981; 1983; Lydon, 1983).

Deposit trace element geochemistry
Feeder or stockwork zone (Large, 1983; Lydon, 1983): iron, lead, and zinc (± gold, boron, and copper). Stratiform ore (Large, 1983; Lydon, 1983): lead, zinc (cadmium), with or without barium (zoned laterally outward from feeder zone (fig. 1). Iron may be enriched within and adjacent to the base-metal sulfide zone (Large, 1983); anomalous concentrations of silver ± arsenic and antimony in sulfosalt minerals (Cox and Curtis, 1977; Taylor and others, 1984) and manganese (outer halo) are also common (Maynard, 1981). Concentrations of mercury are high in some deposits, where it is primarily in pyrite, sphalerite, or sulfosalt minerals (Ryall, 1981).

Ore and gangue mineralogy and zonation
Dominant sulfide ore minerals are sphalerite and galena, although minor chalcopyrite, arsenopyrite, and tetrahedrite are present in some deposits (Large, 1983). The most common gangue minerals are iron sulfide (pyrite or marcasite; less commonly pyrrhotite) and quartz (Meggen, Germany and Red Dog, Alaska). Barite may be present. Numerous other sulfide and sulfosalt minerals have been reported in some deposits (Cox and Curtis, 1977; Large, 1983; Taylor and others, 1994). Relative abundances of major base-metal sulfide minerals vary among deposits and within deposits as a result of zonation. Large (1983) reports that lead-zinc ratios of ore range from approximately 1:1 (Mount Isa, Australia; Sullivan, British Columbia; and Tynagh, Ireland) to 1:8 (Meggen, Germany). The sequence of zonation is generally lead-zinc-(barium-copper) extending outward in laterally zoned deposits and zinc-lead-(barium) extending upward in vertically zoned deposits (Large, 1983; Lydon, 1983). Iron is sometimes enriched at the center of zonation assemblages (for instance, Rammelsberg, Germany and Sullivan, British Columbia) (Large, 1983), or an iron-manganese halo may encircle the base-metal sulfide minerals (Tynagh, Ireland) (Maynard, 1983).

Mineral characteristics
Grain size typically ranges from 15 to 400 microns (McClay, 1983). Primary depositional features are dominated by fine-grain size and common layering; framboidal and colloform pyrite with euhedral overgrowths are common; granular sphalerite, galena and barite are typical. Some deposits (Red Dog, Alaska and HYC, Australia) are characterized by very fine-grained intergrowths of silica and sphalerite (individual sphalerite grains are 0.5 to 50 microns) or sphalerite with other sulfide minerals (<100 microns) (McClay, 1983; Moore and others, 1986). Metamorphism partially or completely replaces primary textures and causes grain size increases. Recrystallization causes porphyroblastic textures in pyrite and sphalerite, barite is recrystallized to an elongate habit, and galena may be remobilized to fill fractures (McClay, 1983).

Secondary mineralogy
Oxidation of deposits may result in formation of iron-rich gossan and ferruginization of wall rocks (fig. 2). Deposits with low iron-sulfide contents have high metal-sulfur ratios, gangue or wall rocks with high buffering capacity, associated gossans have high pH, and gossan profiles are immature. Ore with high iron content, low metal-sulfur ratios in sulfide minerals, and wall rock with low buffering capacity is likely to be associated with low pH water (Taylor, 1984). Goethite and hematite, with minor quartz, kaolinite, and beudantite, are the main minerals in gossan (Taylor and others, 1984). Anglesite and cerussite are the most abundant secondary lead minerals but coronadite, mimetite, nadorite, pyromorphite, and lanarkite have also been reported. Silver halide minerals may also be present. Secondary zinc minerals are rare. Secondary sulfate minerals include jarosite, barite, and alunite. Native sulfur, produced by oxidation of marcasite, is present at Red Dog, Alaska (R.A. Zierenberg, written commun., 1995). Rock may be oxidized to 100 m below the surface (Australian examples), and may extend to 300 m adjacent to major faults and shear zones. Oxidation depth is controlled partly by fracture density near orebodies and presence of pyrrhotite, which is highly reactive with oxygenated ground water (Taylor and others, 1984).

Secondary zinc minerals hemimorphite, smithsonite, and wurtzite, not found in association with other deposits, are present in lime green mosses and as a cement within talus overlying the XY deposit (Howard's Pass, Yukon Territory) (Jonasson and others, 1983; Lee and others, 1984).

Topography, physiography
No generalizations possible. Sedimentary exhalative deposits are widely distributed geographically (from Australia to northern Alaska, to Ireland, for example) and so have completely different physiographies and topographies due
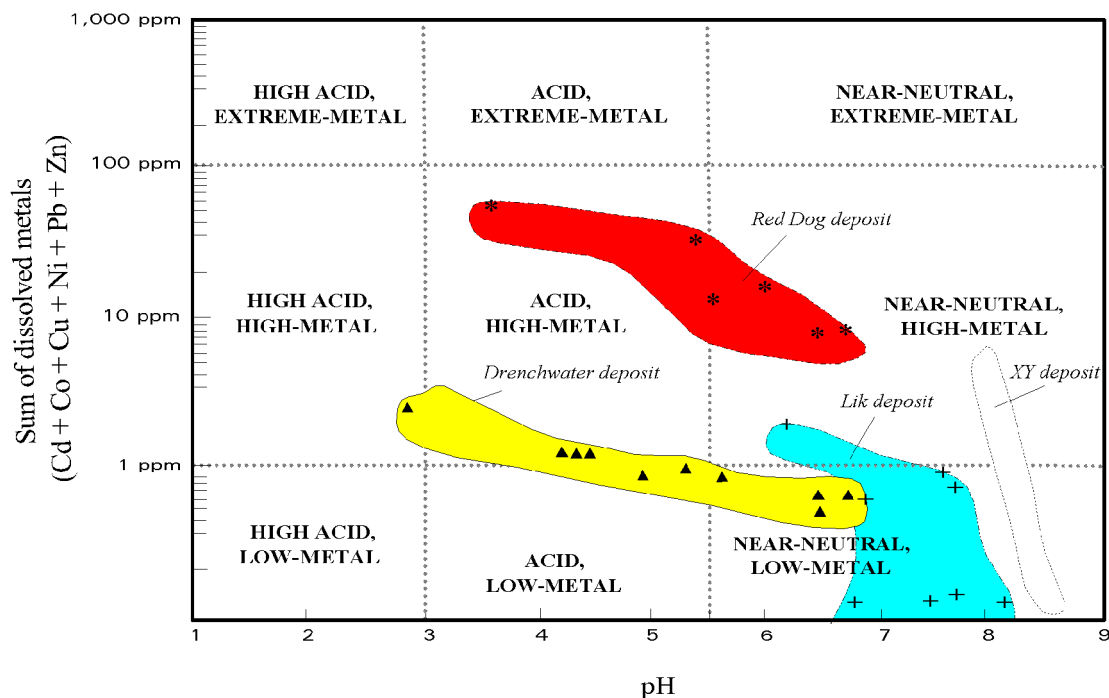
Figure 3. Diagram showing the relation between pH and metal content of water draining sedimentary exhalative deposits (modified from Plumlee and others, 1993).

to weathering process variations.

Hydrology

Hydrologic conditions associated with sedimentary exhalative deposits are highly variable due to extreme differences of their climate settings. Fine-grained clastic host rocks generally have low permeability. Pre-mineralization and post-mineralization fractures may serve as ground water conduits. However, depth of oxidation is dependant on a number of factors including climate, mineralogy of ore, and (or) host rocks.

Mining and milling methods

Underground and open-pit mining have been used historically and in modern times to exploit these deposits. Some sedimentary exhalative deposits contain very fine-grained and intergrown sulfide minerals (for example, Red Dog, Alaska and HYC, Australia) that require fine grinding during ore beneficiation. Base metal sulfide minerals are usually separated by flotation and ore concentrates are smelted. In most cases, concentrates are shipped to custom smelters and therefore do not contribute to environmental impact in the immediate mine vicinity. Large districts, such as Sullivan, British Columbia, are served by nearby smelters (for instance, Trail smelter, British Columbia).

ENVIRONMENTAL SIGNATURES

Drainage signatures

Natural drainage water (Lik, Red Dog, and Drenchwater, Alaska: Dames and Moore, 1983; EIS report for Red Dog; Kelley, 1995; Kelley and Taylor, in press): Cold semi-arid climate--Without carbonate rocks present (Red Dog and Drenchwater), streams draining mineralized areas have low pH (2.8 to 4.7) and elevated dissolved metal abundances, including tens to hundreds of mg/l aluminum and iron and hundreds to tens of thousands of μg/l Mn, Cd, Co, Cu, Ni, Pb, and Zn. Sulfate concentrations, hundreds to thousands of mg/l, in water draining mineralized areas are also many times higher than background. Sodium and barium may be depleted in water draining mineralized areas. Data for deposits with significant associated carbonate rocks in surrounding geologic terrane (Lik, Alaska) are strikingly different (fig. 3). Water draining these deposits is near-neutral to alkaline (pH 6.2 to 8.1) and contains low metal concentrations, except zinc, whose abundances, thousands of μg/l, are enriched in streams draining mineralized areas. Sulfate concentrations, hundreds of mg/l, may also be elevated.

Neutral-pH springwater near the XY deposit (Howard's Pass, Yukon Territory) contains elevated dissolved metal abundances, including tens to thousands of μg/l zinc, tens of μg/l cadmium, and tens to hundreds of mg/l sulfate.

Mine drainage water (Red Dog, Alaska: Beelman, 1993; unpub. data, Alaska Department of Environmental Conservation, ADEC, 1995; Faro, Yukon Territory: Lopaschuk, 1979; Meggen, Germany: Bergmann, 1971; Broken Hill, South Africa: Gulson and others, 1994): Cold semi-arid climate--Immediately after mining began at Red Dog in the Fall of 1990, water draining the mine was extremely acidic (pH as low as 1.7) and contained elevated metal abundances, including from hundreds to thousands of μg/l lead, from hundreds to tens of thousands of μg/l cadmium, and from tens of thousands of μg/l to thousands of mg/l zinc. However, by spring of 1991, these abundances had decreased to pre-mining natural background concentrations (ADEC, 1995). The pulse of metal-enriched mine drainage that followed initial mining was probably the result of dissolution and flushing of a secondary sulfate mineral accumulation that developed as a result of marcasite oxidation in a near surface environment along steep faults (R.A. Zierenberg, written commun., 1995). Mild wet climate--The Meggen, Germany, mine, known in the late 1960s for mine water with high metal ion content and low pH, posed a severe pollution problem (Bergmann, 1971). Elevated metal abundances included hundreds of mg/l aluminum, tens of mg/l manganese, hundreds to thousands of mg/l iron, and hundreds to thousands of mg/l zinc.

Potentially economically recoverable elements: Zinc (as zinc hydroxide produced after treatment of mine water) is economically extracted at the Meggen, Germany, mine (Bergmann, 1971).

Metal mobility from solid mine wastes

Mine dumps may be a source of lead due to soluble secondary lead minerals common in oxidized material. Some of these dumps have recently been reprocessed, resulting in an increased volume of fine-grained lead-rich dust that contains as much as 3 weight percent lead (Gulson and others, 1994); this dust can be important in arid to semi-arid regions with high wind potential.

Bioavailability studies: The most common lead species in soil and dust associated with the Broken Hill, Australia, deposit was identified as a complex Pb, Fe, Mn, Ca, Al, Si, O material (very soluble), with high bioavailability. Other mining areas may have less soluble, and therefore lower bioavailability forms of lead, including galena, pyromorphite, and anglesite (Gulson and others, 1994).

Soil, sediment signatures prior to mining

Cold semi-arid climate: Stream sediment samples (<0.2 mm and <0.5 mm fractions) contain anomalous concentrations of many metals, including as much as ten ppm silver; tens of ppm arsenic, cadmium, and antimony; hundreds of ppm copper and nickel; thousands of ppm manganese, lead, and zinc; and hundreds of thousands of ppm barium (Theobald and others, 1978; Kelley and others, 1992). Soil that overlies mineralized rock contains hundreds to tens of thousands of ppm lead, hundreds to thousands of ppm barium and zinc, tens of ppm silver; and tens to hundreds of ppm copper, but concentrations of other metals, including <2 ppm cadmium, hundreds of ppm manganese, and tens of ppm nickel are low relative to stream sediment abundances (Briggs and others, 1992; Meyer and Kurtak, 1992). The pH of soil directly above mineralized rock may be as low as 3.9 (Briggs and others, 1992). Warm semi-arid climate (Australia): Soil overlying mineralized rock contains hundreds to thousands of ppm copper, lead, and zinc, and tens of ppm silver (Cox and Curtis, 1977).

Potential environmental concerns associated with mineral processing

Mining and milling methods significantly influence potential environmental impacts associated with sedimentary exhalative deposits. Most underground mines dispose of mine waste and mill tailings by backfilling underground workings. Consequently, environmental concerns related to these underground mines may be limited, with exceptions noted below.

Modern mines discharge fine-grained sulfide-mineral-rich tailings into surface tailings ponds that have impermeable linings. Previous tailings discharge methods resulted in significant surface and shallow ground water contamination. Very finely ground, fine-grained and intergrown sulfide minerals may result in highly reactive tailings products.

Until 1967, mine water draining the Meggen, Germany underground mine had a pH as low as 2.5 and contained as much as 1,300 mg/l zinc; this mine water originates by percolation of surface water through the mine. Acidic, metal-rich water draining the mine caused severe pollution in major river systems draining the area. Modern techniques enabled zinc recovery from mine water; mine effluent ceased to be a pollution source (Bergmann, 1971).

Mining and milling activities at the Zawar, India mine have resulted in contamination of stream sediment and floodplain soil (Prusty and others, 1994; Sahu and others, 1994). Stream sediment samples collected as much as 30 km from the mill site contain elevated metal abundances, including thousands of ppm zinc and iron, hundreds of ppm lead, and tens of ppm cadmium. Floodplain soil contains similarly elevated metal abundances.

"Hot muck" was an environmental concern associated with processing ore from deposits with high pyrrhotite abundances that are exposed to air and water. "Hot muck" is the spontaneous combustion of high sulfide ore in the mine. The primary environmental concern is evolved sulfur dioxide. Fires are ignited by the build-up of heat, caused by ore oxidation, in stock piles, or may be triggered by blasting in areas of previously broken ore. Periodically, air emission can exceed 9.5 ppm SO_2 (Brown and Miller, 1977; Good, 1977); SO_2 release can acidify water in areas downwind from release site. Because hot muck is easily avoided by proper blasting techniques, it does not pose significant risks in modern mining operations.

In some cold climates, it may be necessary to store wet ore, such as that produced from the Faro, Yukon Territory, mine, prior to crushing. If the ore is stockpiled too long, oxidation may ensue (Lopaschuk, 1979), which may cause increased metal concentrations, especially lead, in drainage water.

Smelter signatures

Smelting was and is commonly used to process sedimentary exhalative ore. Several studies focus on the correlation between lead in soil near smelters and lead in the blood of children (Gulson and others, 1994). Smelting may produce SO_2-rich and metal-rich emissions, which may increase acidity and foster accumulation of heavy metals in downwind areas.

Climate effects on environmental signatures

Sedimentary exhalative deposits are widely distributed geographically (from Australia to northern Alaska, as well as Ireland) and therefore are in highly variable climatic regimes. The effects of various climate regimes on the geoenvironmental signature specific to sedimentary exhalative deposits are not known. However, in most cases the intensity of environmental impact associated with sulfide-mineral-bearing mineral deposits is greater in wet climates than in dry climates. Acidity and total metal concentrations in mine drainage in arid environments are several orders of magnitude greater than in more temperate climates because of the concentrating effects of mine effluent evaporation and the resulting "storage" of metals and acidity in highly soluble metal-sulfate-salt minerals. However, minimal surface water flow in these areas inhibits generation of significant volumes of highly acidic, metal-enriched drainage. Concentrated release of these stored contaminants to local watersheds may be initiated by precipitation following a dry spell. Although it is commonly assumed that the extent of sulfide mineral oxidation and weathering in cold regions underlain by permafrost are minimal, data from northern Alaska show that metal dispersion from ore deposits in surface water is significant.

Geoenvironmental geophysics

Induced polarization methods can provide qualitative estimates of sulfide mineral contents and grain size, which strongly influence potential for generation of acidic, metal-enriched water. Electrical techniques (King and Pesowski, 1993) and ground penetrating radar (Davis and Annan, 1992) can be used to delineate low resistivity anomalies produced by acidic, metal-enriched water that may be associated with this deposit type.

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